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## **New Technologies for a Future Superconducting Proton Collider**

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## New Technologies for a Future Superconducting Proton Collider

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### Introduction

New more economic approaches are required to continue the dramatic exponential rise in particle accelerator energies as represented by the well-known Livingston plot. The old idea of low-cost, low-field iron dominated magnets in a small diameter pipe may become feasible in the next decade with dramatic recent advances in technology:

- high  $T_C$  superconductors operating at liquid  $N_2$  or  $H_2$  temperatures
- advanced tunneling technologies for small diameter, non human accessible tunnels
- accurate remote guidance systems for boring machine steering
- industrial applications of remote manipulation and robotics
- digitally multiplexed electronics to minimize cables

There is an opportunity for mutually beneficial partnerships between the High Energy Physics community and the commercial sector to develop the necessary technology. This will gain public support, a necessary part of the challenge of building a new, very high energy collider.

Project information can be found at  
<http://www-ap.fnal.gov/PIPE/>

### Historical Note

The concept of building an accelerator in a pipe was clearly presented by Fermilab's Founding Director, R. R. Wilson at the Snowmass Conference in 1982.<sup>1</sup>

"Whether the next large proton accelerator (20 TeV ?) is built on a national basis or as an international effort, to be affordable, innovations in construction must be made. The design of a super-ferric magnet ring buried in a pipe in the ground is explored to see what reductions in cost might result."

"...superferric magnets (an old idea) have the advantage of simplicity, of being more sparing in the use of superconductor, less sensitive to the position of the superconductor, easier to construct, and perhaps more reliable to use."

Relevant technologies have emerged and grown rapidly since Snowmass 1982. Extrapolations of these

technologies can bring this dream to reality in the next 10 - 20 years.

### **Project Goals**

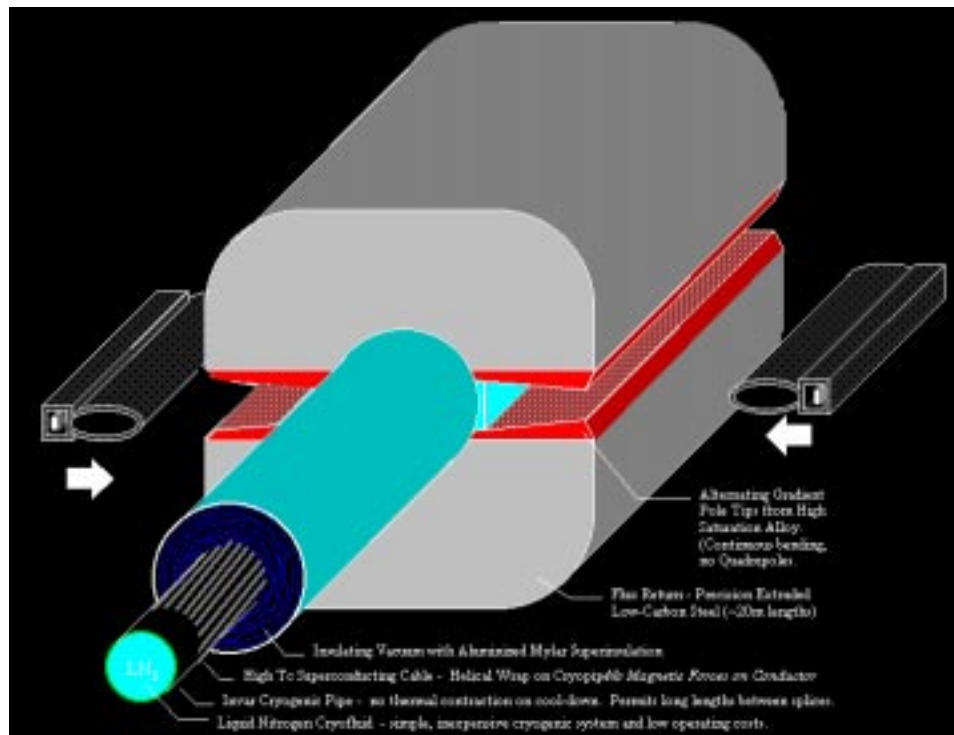
- Define an affordable path to 100 TeV per beam (200 TeV in the center-of-mass). 1 TeV= $10^{12}$  electron-volts.
- One-tenth the cost per TeV (beam energy) of the SSC or LHC including collider enclosure.
- As few surface accesses as possible, dictated by political as well as cost considerations.
- A site-specific proposal to use the Fermilab Main Injector or Tevatron as the injector. The multi-billion dollar investment in Fermilab must not be discarded as was the case for the SSC project.

The Accelerator is logically divided into two sections:

- Magnet enclosure: a long ring (“pipe”) deep underground and too small for human access. This tunnel would contain only accelerator magnets and transmission lines.
- A large on-site human accessible hall providing all functions requiring human intervention: detector, transfer lines from injector, RF, beam abort, staging areas for the remote control repair vehicles, etc. A significant part of the total project cost will be in this large underground hall containing the “conventional” accelerator equipment.

### **Magnet**

The key element in a new large hadron collider is the magnet. A promising candidate for the magnet is the “double-C transmission line magnet” proposed by G. W. Foster,<sup>2,3</sup> shown below.



This magnet has the following characteristics:

- Single turn magnet driven by a SC transmission line carrying 60 kA.
- Twin 1.5 cm apertures for a p-p collider.
- Warm iron, warm bore design. Cold mass is small and cool down will be fast.
- Due to the symmetry of the design there are no forces on the conductor. This simplifies the cold mass support (“spiders”) and allows a low heat leak design. It is similar to a liquid cryogen transfer line.
- The conductor sees  $\leq 1$  T. Existing commercially available high  $T_c$  conductors can carry the current density required if the coil is cooled to 20 K. Conductors under development may carry this current at 77 K (LN<sub>2</sub>)
- Development of this magnet type parallels ongoing industrial development of high- $T_c$  superconducting power transmission lines which will come to fruition in this decade.
- Field can be mapped prior to beam pipe installation due to the “C-magnet” design.
- There is access to magnet pole tips for shimming/trimming/survey.
- There is access to the vacuum system, BPM’s etc., without touching cryogenics. The vacuum system will be an all aluminum system extruded in long lengths.

### **Collider Parameters**

Initial parameter sets for 100 TeV x 100 TeV colliders have been developed by Steve Holmes<sup>4</sup>, Wm. Barletta<sup>5,6</sup>, and David Neuffer<sup>7</sup>. Barletta proposes  $6 \times 10^{10}$  protons/bunch, 190,000 bunches, and a luminosity of  $10^{35}$ . Circumference of the collider is 1160 km ; field 2.0 T. 90% of the circumference is bending.

One way to obtain this high “packing fraction” (75% is a more typical number) is to use an alternating gradient lattice. This lends itself to long, identical modules making installation and repair easier. There are no quadrupoles to interrupt the “transmission-line” cryostat, and nearly no interruption of the bend field allowing one to aim for a packing fraction >90%.

Neuffer<sup>7</sup> develops several lattices, both separated and combined function, and for phase advance/cell of 30°, 60°, and 90° and half-cell lengths varying from 200 - 300 meters. Holmes<sup>4</sup> proposes combined function with 60° advance and 290 meter half-cell length.

### **double-C magnet vs. H-magnet**

With an H-magnet, the return current is naturally in the magnet, whereas in the double-C design a separate return lead in the collider enclosure is necessary to avoid a disturbing large dipole, to allow dividing the large circumference into separately powered loops and to criss-cross the current (and beams) in an even number of crossing points and maintain equal circumference for the two beams. The double-C magnet is “naturally” a pp collider. The return current in the C-magnet case causes a slight asymmetry (e.g. top/bottom if the return is placed above the collider). This needs to be evaluated and corrected for.

In H-magnets the challenge is the large magnetic forces (on the cold conductors) in most designs (although there are coil locations that minimize this problem). With large forces, the “spiders” supporting the cold mass need to be strong and frequently spaced thus increasing the heat leak. A gradient H-magnet could be considered; otherwise quadrupoles

would have to be developed. In the H-magnet, four small diameter cryopipes would carry the current. For pp, two H-magnets would be required.

In iron magnets, of either the double-C or H- design the energy is in the gap where needed; the proposed 1.5 cm (vertical) x 3 cm gap has a good field region of 1.5 cm x 2 cm. This is to be compared to cos $\theta$  designs where the good field region is less than the physical aperture.

It is now possible to obtain solid steel extrusions with good tolerances and in long lengths. ANSYS calculations of eddy currents indicate laminations are unnecessary for a machine with a 5-20 minute ramp.

High-saturation alloy pole tips would permit  $B > 2T$ . This issue will be settled

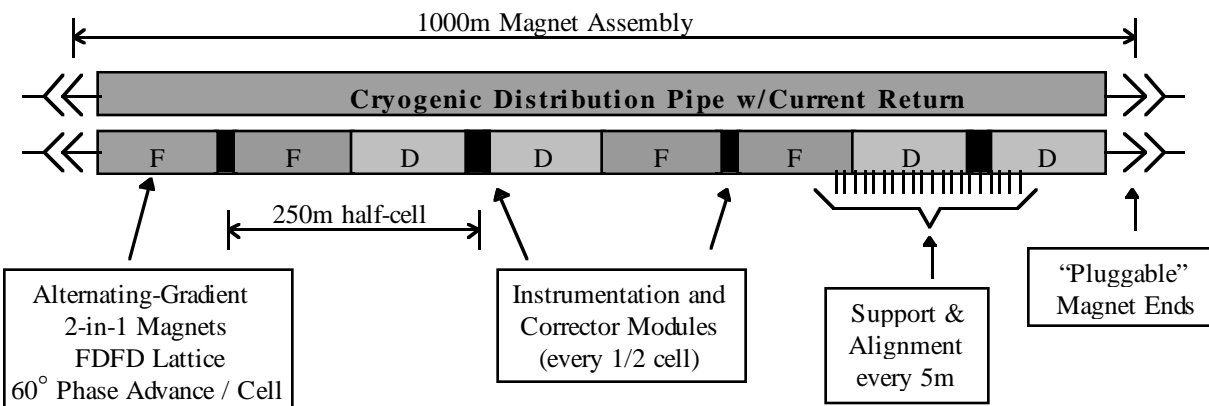
by looking at the cost advantage of a slightly higher bending field and smaller circumference.

### **Demonstration/Test Facility**

This is now under construction as a joint project of the Technical Support Section and the Accelerator Division. A current transformer, built from a modified accelerator magnet, will be used to excite the 60 kA current loop. The goals of this facility are to

- demonstrate the concept using helium and NbTi conductor
- provide a test bed for field quality demonstration and pole tip development
- be compatible with an eventual upgrade to high- $T_c$  conductor.

## **TRANSMISSION LINE MAGNET LAYOUT**



... each magnet assembly is responsible for 200 GeV ECM

### **The Nuclotron**

There is an existing superferric magnet synchrotron, the "Nuclotron" at J.I.N.R., Dubna (Russia).<sup>8</sup> It is a separated function lattice, accelerates particles to 6 GeV per nucleon. The H-type

magnets operate over a field range of 0.03 T to 2.0 T or a factor of 67. The builders of that machine have made an extrapolation using their design to a pipetron<sup>9</sup> with a total heat leak (at liquid helium temperature) of 500 mw/meter.

### Accelerator and instability issues

Gerry Jackson<sup>10</sup> outlined the accelerator dynamics issues that need to be addressed in considering this very high energy, low revolution frequency collider.

To avoid tune modulations at harmonics of the local line frequency (60 Hz), he proposes, as does Barletta<sup>5</sup> to make the revolution frequency an integer harmonic of the line frequency.

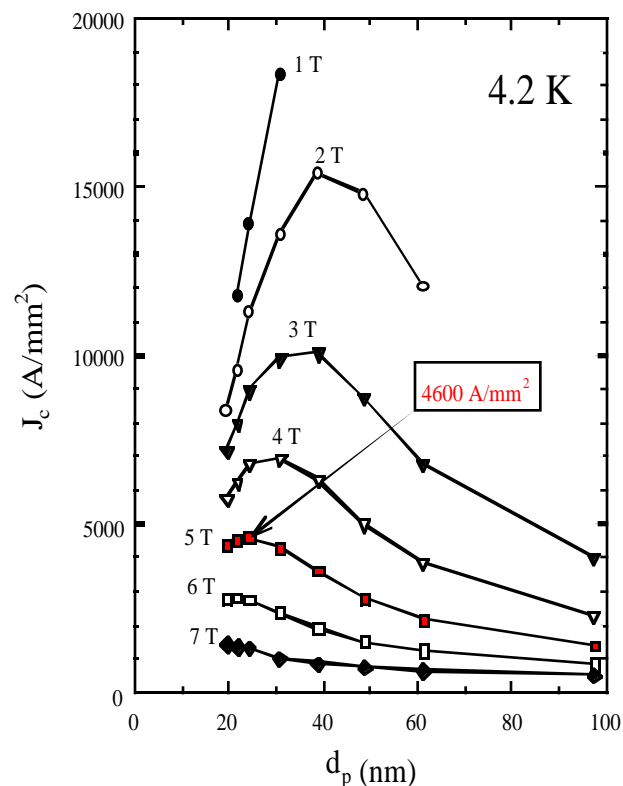
One of the most serious issues is emittance growth driven by noise. This noise spectrum rises logarithmically as the frequency becomes lower. There are two approaches to this problem; both must be investigated:

- Passive suppression of emittance growth by mechanically mounting the magnets to isolate them from sources of rapid motion and/or cryogenic/electrical system design eliminating sources of noise.
- Active suppression using feedback requires extremely low noise pickups and preamplifiers and damping times short compared to induced decoherence times. Suppression of electro-acoustical noise in a 100 TeV machine is discussed by Lambertson.<sup>11</sup> Problems of emittance growth in the Tevatron have been systematically studied and the sources of growth eliminated or reduced in importance. Experiments in the Tevatron can be used to verify calculations and test feedback schemes.

Magnet aperture requirements will be partly determined by the resistive wall instability and the method used to deal with it.

### Superconducting Cable

Current status and a comparison of low  $T_c$  and high  $T_c$  materials was summarized by Larbalestier.<sup>12</sup> NbTi with artificial pinning centers (APC) are attractive for the double-C design where the field at the conductor is relatively low. The graph below, from Larbalestier's talk shows  $J_c$  (in amps/mm<sup>2</sup>) vs.  $d_p$  (pinning center spacing in nanometers) from 1 to 7 T for Nb-47wt%-Ti (APC with 24 vol% Nb of pins), showing a new world record for current densities for round strand.



High temperature superconductors (HTS) are a key technology that was not available to the SSC or LHC. Multifilamentary BSCCO conductors are commercially available now, and prototype biaxially aligned YBCO monofilament tape conductors exist and are being developed at Los Alamos and Oak Ridge National Laboratories.

BSCCO-2212 and BSCCO-2223 when they are operated at  $<20\text{K}$  offer enormous capability. Their current carrying capacity is high and rather independent of field. BSCCO-2223 is currently being used at Pirelli Cable Corporation under an EPRI/DOE contract to develop a prototype superconducting power transmission line.

The initial design of the pipetron double-C magnet calls for a single turn carrying 60 kA. 1 cm wide Los Alamos tape has a critical current at 77 K and 0 field of about 200 amps, so 300 conductors wrapped around a 1 in diam pipe would provide a 50 kA cable.

Commercially available conductor for use in  $\text{LN}_2$  Cooled Transmission lines is getting better all the time. A liquid nitrogen Cryogenic System is *much* cheaper than helium and *much much* cheaper than superfluid He which will be used in LHC. Liquid hydrogen is also an attractive possibility especially since our goal is to have the accelerator enclosure non-human accessible and it could be filled with dry nitrogen gas.

### **Cryogenics in the double-C design**

Cryogenics baseline parameters were presented by Mazur at the Indianapolis meeting<sup>13</sup> and preliminary calculations have been done by McAshan<sup>14, 15</sup>. A baseline is based on 60 kA lines (one drive loop, one return loop) using NbTi superconductors. The length of one cryogenic loop is 40 km, requiring a building and 18 kW refrigeration plant every 80 km. Thus for a 100 TeV collider, approximately 1000 km in circumference, 12 above ground refrigeration plants would be required. With a Carnot efficiency of 1/200, this translates to 3.6 MW ; for a 100 TeV collider, a total of 43 MW of wall power. If  $\text{LN}_2$  was used wall power would be  $< 3\text{ MW}$ .

After each 1000 meter long magnet module (see diagram above) is placed a 3 meter long recool. Assuming a heat leak of 50 mw/meter is attained, the temperature rises from 4.3 K to 4.6 K from one end of the magnet module to the other. Inside the accelerator enclosure will be three lines for the cryogenic system: a drive conductor line in the magnet, a main liquid cryogenic transfer line, and a warm gas return line which consists of a 10 cm diameter pipe.

The warm gas return line is used for cooldown and quench recovery. The total heat leak budget is 200 mw/meter (for magnet and return). Multilayer insulation results achieving this low value have been published by several authors. The challenge will be to achieve this on the large scale required.

### **Remaining challenges:**

- cryogenic connections and remote assembly
- thermal expansion of the cold components (we may use an invar pipe in the magnet)
- electrical insulation of the magnet drive conductor
- controls and instrumentation

When HTS becomes available with suitable properties at acceptable costs (that may already be true), it may be possible to use hydrogen (or even nitrogen) refrigeration. The hydrogen refrigerator is likely to be smaller, less expensive, and to have lower operating costs than the helium refrigerator. Hydrogen has a latent heat of 450 joules/gram, 22 times that of helium. Consequently, the flow rates required for the same heat leak are smaller and the pipe sizes required in the main transfer line in the collider enclosure



are considerably smaller resulting in substantial cost reductions. Mazur's paper<sup>13</sup> compares pipe sizes:

radius in cm.	helium	hydrogen
liquid line	3.4	1.1
cold gas line	8.5	3.7

Quench protection parameters have been worked out by Koepke<sup>16</sup>. The type of superconductor (LTS or HTS) is not yet determined so Koepke has used a universal approach that depends only weakly on the operating temperature of the superconductor. The superconductor must be in good electrical contact with cable copper area of 1 cm<sup>2</sup>. The design of the quench system/power supply system is mainly driven by the allowable peak temperature, assumed to be 500 K, and the peak voltage to ground, assumed to be 2 kV.

Power supplies and switched series resistors are evenly spaced to minimize voltage to ground. The 40 km (4 TeV) loops assumed for the cryogenic (helium based) system are also reasonable for the power supplies and dump resistors. A dump resistor extracts 160 MJ with a time constant of 1.3 seconds.

With a ramp time of 1000 seconds, the ramp voltage is 4 volts, and the peak ramp power is 200 kW.

### **Synchrotron radiation**

As the energy increases beyond 20 TeV per beam, synchrotron radiation can have a substantial positive impact on collider performance. This was explored for a 30 x 30 TeV p-p collider with 10<sup>34</sup> luminosity at the Workshop on Future Hadron Facilities in the U.S.<sup>17</sup> With a magnetic field of 12.5 T, damping times were 4.7 hours transverse and 2.3 hours longitudinal. One must remove the heat load generated within

the cold bore magnets. Beyond 30 TeV per beam and at luminosities above 10<sup>34</sup>, synchrotron radiation becomes a serious, if not fatal problem for the cold bore cos $\theta$  dipole.

Turner<sup>18</sup> starts with Neuffer's parameters<sup>7</sup> although his beam tube diameter of 4 cm is larger than has been assumed elsewhere in this paper. Damping time is 20.7 hrs, so this will play a minor role in shrinking the emittance during the store, since it is anticipated that store times will be roughly half-day. The synchrotron power radiated is 0.21 watts/meter. This is relatively weak compared to contemporary proton and electron rings and has both advantages and disadvantages. The decrease in photon intensity in the pipetron compared to contemporary electron storage rings is compensated by a slower cleanup rate for the vacuum system, so similar linear pumping speeds are required.

Beam tube conditioning times to achieve vacuum limited luminosity lifetime > 100 hours and scattered beam power < 0.1 watts/meter globally and < 1 watt/meter locally are reasonably short. More investigation is needed to set the limits on beam power allowed by the superconducting transmission line.

There appear to be large safety margins for ion desorption stability and beam induced multipactoring.

### **Vacuum system in the double-C design**

Ishamaru<sup>19, 20</sup> has based his conceptual design on an aluminum alloy vacuum pipe. It has the features of low cost and high reliability. Continuous aluminum extrusions can be obtained in long lengths: >250 m. One of the key

design features is to have no bellows which reduces costs and impedances significantly. The chamber is periodically anchored to the iron to control thermal effects. Finite element analysis shows this system will work.

The chamber, 1.5 mm thick, is high resistive aluminum alloy. It is a clad structure with 100 microns of 99.99% pure aluminum on the inner surface (to reduce resistive wall effects).

A high-conductance side chamber for pump down contains the distributed non-evaporable getter (NEG) pump, a standard solution for electron machines.

Either distributed ion pumps or NEG strips with lumped ion pumps look technically feasible for the 200 TeV superferric warm bore pp collider.

An outgassing rate of  $\sim 10^{-13}$  Torr-liters/sec/cm<sup>2</sup> can be achieved utilizing a chemical cleaning process procedure at 70°C, and 1 hour mild baking at 350°C during NEG strip activation.

In the center of each 250 meter length (at  $\beta_{\text{max}}$ ) will be placed the x-y beam position monitor (BPM), lumped ion pumps for pumping noble gasses, a roughing port, and the NEG strip power feedthrus.

At the end of each 1 km magnet will be placed a quick disconnect, and gate valve. The magnet can be inserted into the collider enclosure under vacuum.

### **Geology of the Fermilab Region.**

Gross<sup>21</sup> has described the suitability of the Fermilab site and region around it for a new large collider project.

Site conditions at Fermilab are well understood. The Illinois State Geo-

logical Survey (ISGS) has extensive data on the regions under consideration from several hundred-thousand drill holes, and additional data compiled when there was active consideration given to siting the SSC in Illinois. Neighboring mid-West states have similar extensive information relevant to a large project of this sort.

There are predictable rock and tunneling conditions, relatively homogenous rock mass, seismically stable with no movement in recorded history. There is a vibration free environment, important to minimize emittance growth problems. There are no settlement problems at the depths being considered.

Even the largest ring we have considered, 1100 km in circumference is still in glaciated terrain. The Silurian dolomite under Chicago and the Ordovician dolomite under Fermilab are quite uniform. The large regional extent of dolomite can serve as an excellent host for a tunnel or horizontal drill hole in the Fermilab region.

There is extensive local tunneling experience: 72 miles of tunneling experience in Chicago, using TBM's (tunnel boring machines); 266 shafts constructed for TARP (Tunnel and Reservoir Project). The total volume of rock excavated with TBM's in the Chicago area already greatly exceeds that required for the 100 TeV machine.

In a glaciated region, groundwater is typically present in the glacial drift and in the uppermost few meters of bedrock. In the bedrock beneath Fermilab, the rate of movement of groundwater varies by three orders of magnitude.

The dolomite of the Galena-Platteville does not yield much water (water moves at only 1 ft/year), whereas the sandstone is a high quality aquifer. Therefore, the dolomite is attractive for a collider project. Major tunnels under Milwaukee and Chicago, constructed in the dolomite, have such low seepage rates that they are unlined.

### **The Accelerator Enclosure**

Iseley<sup>22</sup> describes Trenchless Technology and its rapidly growing importance as a practical solution to expansion and repair of underground utilities. This is an area where not only can the pipetron benefit from this technology as its capabilities expand but can also be a catalyst to this environmentally crucial industry.

There are two competing commercial technologies with potential application to the pipetron: microtunneling and horizontal directional drilling. These technologies have emerged in recent years, motivated in part by the need to build new and rebuild old infrastructure with minimum surface disturbance. These technologies are already in the tens of billions of dollars/year category and growing rapidly.

### **Features of Microtunneling**

- a trenchless technology for constructing pipelines to very close ( $\pm 1$  inch) tolerances.
- a remotely controlled, laser guided, system; personnel entry not required. Microtunneling is essentially a scaled-down version of the "Tunnel Boring Machine." (TBM) technology used to bore the Chicago Deep-Tunnel project, and later, a portion of the SSC tunnel.

- used to install pipelines in a single pass operation in lengths up to 2,000 ft, and in diameters from 6 in. to 10 ft.
- typical production rates are 30 to 60 ft/day; rates of >200 ft/day have been achieved.
- can be used in a variety of ground conditions from soft clay to rock, above or up to 100 ft below the water table.
- Microtunneling costs continue to drop.

### **Microtunneling issues for the pipetron**

Are liners needed? This depends on the rock, and as indicated, seepage rates are very low in the dolomite layers some 300 ft below the surface in the Fermilab region. Current R&D efforts in the microtunneling industry are aimed at remotely installed liners, either spray on or liners that are in arches that can snap together.

Another issue are the cutters for a hard rock tunneling machine. They need to be changed periodically and this leads to manned access or to a large number of vertical shafts. Even extrapolating to the future, we might need an access point as often as every 2 km. Concepts under discussion would make it possible for two microtunneling machines to pass each other; thus one could be pushing ahead, while the other is brought back for servicing. These are difficult problems and require considerable R&D effort to solve, but would have a large payoff to industry.

Removing the "muck" is another challenge. Current methods use a

conveyer, dump cars (as in mining technology) or a slurry. Hydraulic impedance increases as bore is longer and weight of the cables/hoses mounts up. More discussion and design work is needed, but at this juncture, the leading idea is installation of rails as the microtunnel machine advances and then use these rails both for muck removal during accelerator enclosure construction and later for magnet installation.

Most microtunnels have been straight or gently curved. Laser ring gyro systems with accuracy of 2 inches are under development. Microtunnels that go in curves and follow terrain (as our large collider will likely do) are just beginning to be built, mostly in Europe.

The first microtunnel in the U.S. was built in 1984. Atalah and Hadala<sup>22</sup> have compiled the cumulative installed microtunneling in North America (in kilometers) of all types with projections for 1996 and 1997 and shows a doubling time of ~ 2.5 years.

#### Features of Horizontal Directional Drilling

- Is a U.S. invention developed primarily for oil and gas exploration, in contrast to microtunneling where until recently the advances have come mainly from Europe and Japan.
- May be more likely to work for us than microtunneling because already today, much longer distances between access shafts are possible. Michels Pipeline, one of the large U.S. companies has drilled 5200 feet. Horizontal drills up to 5 miles are being planned.

- Usual technique is to drill a 10 - 12 inch diam pilot hole, then back ream and enlarge the hole. The drill string is used to pull the finished pipeline into the ground from the far end of the hole. Diameters up to 48 inches are being done.
- Generally goes from the surface, down at 30° - 45°, under, e.g. the Mississippi River, and then back up to the surface.
- Can drill through rock at high speed. Often drilled by a fluid-driven motor mounted downhole directly above the bit.
- A downhole instrument package provides location of the drill bit so that the hole's direction can be controlled.
- .
- Thousands of horizontal wells are drilled each year. The cost of horizontal drilling continues to drop.

#### Horizontal Drilling Issues

The biggest problem with horizontal drilling is the accuracy, currently  $\pm 1$ -2 feet. Density variations in the rock cause the drill to veer from the desired direction. This is clearly not good enough for our application although the distance between access shafts is much greater than with microtunneling. However, there is active research underway in improving accuracy of guiding the drill head.

#### The Construction challenge.

In order to interact more closely with the Trenchless Technology industry Fermilab has joined the North American Society for Trenchless Technology.

As we develop the parameters and concepts further we will at the same time explore partnerships with industry to work on innovative ways for

- longer distances between shafts
- “umbrella” machines which “unfold” at the cutting face
- remote cutter changing
- remote liner installation
- long-distance muck removal strategies
- guidance and survey
- terrain following

### **The Collider Enclosure**

Preliminary enclosure cross sections by Mike May<sup>24</sup> assume a diameter of 3 to 4 feet. As indicated above we do not yet know whether the microtunneling or horizontal directional drilling approach will be chosen. Regardless of this choice, one could consider dividing the collider construction into 2 phases:

phase I -- enclosure construction  
phase II -- collider installation

During phase I we might relax the stringent “non-human accessible” requirement, in which case cost optimization might indicate a larger diameter pipe. In current practice, 36 inch (90 cm) is regarded as the minimum diameter for manned access into long industrial pipelines in Europe and in the U.S., and 32 inch (80 cm) in Japan<sup>25</sup>.

Electrical services need to be provided for the “toy” train that does muck removal, and the robots that install and repair accelerator components. One concept has bare, high voltage bus either on the ceiling or bottom of the enclosure, with the tunnel vehicles extracting power from the bus, much as is done with a subway. What needs to

be decided is what is the maximum voltage that can be handled subject to the problems of dirt and moisture. The vehicles themselves will carry step-down transformers.

Robotics (more correctly remote manipulation) are now being used for repair of sewer pipes ranging from 8 to 30 inch in diameter with access every 300 - 400 ft via manhole. The robots cut holes, put in patches, cut roots out, install new lateral connections, etc. This is a rapidly expanding industry. Virtual reality consoles on the surface will aid complex work deep underground. The operations challenge will be to learn a new way of working with increased emphasis on reliability.

### **Surface penetrations**

As discussed above, a first look at cryogenics and power supply/quench protection requirements are that an access shaft and surface building will be required every 80 km around the ring. Depending on evolution of the tunneling/boring industries and detailed cost optimization not yet done, additional accesses to the surface may be required. Clearly the fewer of these the better. Some of these additional access shafts may not need human access, but would be bore holes for surveying, or running cables of various kinds down to the enclosure.

### **Monitoring and control**

There is room here for a great deal of innovation to reduce costs, and increase reliability. Can one (or a small number of) multiplexed fiber optic links control and monitor the entire collider? What about radiation damage to the fiber and the electronics? As mentioned above we anticipate simple packages containing ion pump, ion pump power supply, beam position monitor, beam loss monitor, and

electronics every 250 meters. This frequency gives redundancy. Correction magnets could be simply iron C-blocks of the required pole tip shape, driven by the same 60 kA main drive conductor, and moved (even during the ramp) by stepping motors.

### **An electron option**<sup>26</sup>

Given a very large radius of curvature enclosure, one may well ask, if, in the CERN tradition of LEP/LHC, one couldn't put an  $e^+e^-$  collider in the same pipe. This is an interesting idea that needs discussion. Simple minded  $E^4/R$  scaling from LEP allows an  $e^+e^-$  collider in the pipetron enclosure to be above the  $t\bar{t}$  and possibly Higgs threshold for the same total RF voltage as LEP II. The required dipole strength is only 100 gauss.

### **The path to 200 TeV c.m. energy**

There are many possible paths between today and what might become a reality 20 years from now. Constraints come from High Energy Physics, magnet economics, and politics. Considerable discussion and hard work is needed to choose the best path.

Some of the issues:

- is there a high-energy physics justification (or an accelerator physics need) for an intermediate energy ring?
- given LHC what should that energy be?
- over what magnetic field range can a usable good field be obtained; this determines the injection energy.
- what are reasonable filling times and ramp rates?
- should we maintain antiproton-proton capability in the next (intermediate) stage?

Holmes<sup>4</sup> suggests a sequence from the Tevatron injecting into a 2 TeV site filler/buster, and then into the final collider, a factor of 50 in magnetic field. The Tevatron operates over a range of 7 in magnetic field. The SSC originally was to have operated over a range of 20 but that was later changed to 10. HERA runs over a factor of >30. Conductor dominated SC magnets are limited by persistent currents whereas iron dominated magnets are not. The Fermilab Main Ring has operated over a range of 57, and the Nuclotron magnetic field range is >60. However, the Main Ring and Nuclotron are not storage rings; the Tevatron and SSC are superconducting rings but use cos $\theta$  dipoles.

### **Next steps**

Begin a vigorous R&D plan to attack, in parallel many of the issues: work on accelerator dynamics, develop the physics case and the preliminary detector parameters, do R&D on magnets including the use of HTS, and together with industry work on tunneling and robotics.

Form partnerships with the private sector and start building public support. To gain this support:

- The cost, measured in \$/TeV must be significantly lower than other projects, and also in absolute terms must be a reasonable amount. A very preliminary look at the major cost drivers (quantities of superconductor, mass of the magnet, complexity, vacuum system, collider enclosure volume, stored energy etc.) give rise to optimism that this goal is achievable.

- There must be some real benefits to society from the R&D leading to this project and also in its execution. These benefits might include shared use of the collider enclosure for infrastructure. The capabilities developed may open new markets for the private sector.

today. It will rely for its success on the synergy between the physics goal of reaching 200 TeV in the collision center-of-mass, and the economic and environmental goals of the trenchless technology, superconducting power transmission, and industrial robotics industries.

This project was conceived with the aim of pushing the energy frontier (distance scale) a factor of 100 further than it is

## **References**

\* = Mini-Symposium, "New low-cost approaches to high energy hadron colliders at Fermilab, May 3, 1996 at the APS Annual Meeting

1. "Superferric magnets for 20 TeV," R. R. Wilson, Proc of Snowmass 1982 Conference, page 330.
2. "Superferric magnets and prototype work at Fermilab," G. W. Foster, \*
3. "Double-C Transmission Line Magnet," G. William Foster, internal note, March 1996.
4. "Parameters and layout of a low field large hadron collider," Steve Holmes, \*
5. "Overview of parameters for a large hadron collider," W. A. Barletta, \*
6. "Maximizing the Luminosity of Hadron Supercolliders at 10-100 TeV," W. A. Barletta, in Supercolliders and Superdetectors, World Scientific (1993).
7. "Discussion of Parameters, Lattices, and Beam Stability for a 100 TeV low-field Collider," David Neuffer, Fermilab TM-1964, March, 1996.
8. "Cryogenic system of the Nuclotron -- a new superconducting synchrotron," A. M. Baldin et al, Advances in Cryogenic Engineering, **39**, 501 (1994).
9. "A 100 TeV Synchrotron/Collider based on the Nuclotron-type Cryomagnetic System," \*
10. "Accelerator Physics in a large superferric collider," Gerry Jackson, Mini-Symposium, \*
11. See G. Lambertson (p. 151), G. Jackson (p. 169), R. Cappi, G. Lambertson, L. Vos (p. 181) and W. Chou, J. Peterson (p. 188), Supercolliders and Superdetectors, World Scientific (1993).
12. "Challenges and Opportunities for the use of High Temperature Superconductors for Particle Accelerators," D. Larbalestier, A. Gurevich, R. Heussner, E. Kadyrov, P. Lee, M. Naus, A. Squitieri, \*
13. "Cryogenics baseline parameters," Peter Mazur, \*
14. "Cheaper Collider Piping Sizes: Helium Temperature Case," M. McAshan, int note, Jan 22, 1996.
15. "Line Sizes for Hydrogen Cooling," M. McAshan, internal note, March 6, 1996.
16. "Quench protection," Karl Koepke, \*
17. Proceedings of the Workshop on Future Hadron Facilities in the U.S., Fermilab-TM-1907 (1994). see "Workshop Summary," S. D. Holmes, page 1, and "30 x 30 TeV-Summary Report," A. Chao, G. Dugan and M. Harrison, page 9.
18. "Synchrotron radiation in a large, warm-bore collider," William Turner, \*
19. "Low cost warm bore vacuum chamber options," Hajime Ishimaru, \*
20. "Conceptual Design Study for a very low cost aluminum alloy vacuum chamber in a high energy low-field collider," H. Ishimaru, preprint, April 9, 1996.
21. "Geology in the Fermilab Region," David L. Gross, \*
22. "Microtunneling and horizontal directional drilling," Tom Iseley, \*
23. "Microtunneling database for the USA and Canada from 1984 to 1995," Alan Atalah and Paul Hadala, report from the Trenchless Technology Center, Louisiana Tech University.
24. "Design concepts for remote installation and repair," Mike May, \*
25. "Pipejacking and Microtunneling," James Thomson, p. 63. Blackie Academic & Professional (1993).
26. see discussion in "Utilization of the Fermilab site for a future accelerator," Fermilab TM-1975, in prep.